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13. ABSTRACT *(Maximum 200 words)*

This final report encompases the following research results:

- In-situ reactive sputter deposition of nanometer-smooth superconducting BSCCO thin films;
- New method of ozone detection for use with reactive thin-film growth;
- Fabrication of and detailed noise properties of thin-film dc BSCCO SQUIDs;
- Power-law scaling of the longitudinal and transverse Hall resistivities due to vortex motion in YBCO, with implications for the nature of the vortex state;
- Measurement of the ac screening response of 2212 BSCCO crystals, and interpretation within electromagnetic skin depth effects;
- Vortex flux creep and high-magnetic-field critical currents of epitaxial YBCO thin films.

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to the Office of Naval Research

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List of Papers Published in Refereed Journals:

"Flux Creep and High-Field Critical Currents in Epitaxial Thin Films of $YBa_2Cu_3O_7$", J.D. Hettinger, A. G. Swanson, W. J. Skocpol, J. S. Brooks, J. M. Graybeal, P. M. Mankiewich, R. E. Howard, B. L. Straughn and E. G. Burkhardt, *Phys. Rev. Lett.* **62**, 2044 (1989).

"Transport and Structural Properties of Bi-Sr-Ca-Cu-Oxide Thin Films Prepared by Reactive Magnetron Sputtering", D. W. Face, J. T. Kucera, J. Crain, M. M. Matthiesen, D. Steel, G. Somer, J. Lewis, J. M. Graybeal, T. P. Orlando, D. A. Rudman, *IEEE Trans. Mag.* **25**, 2341 (1989).

"Bi-Sr-Ca-Cu-Oxide Thin-Films with T_c is Greater than 100K and DC SQUIDs", D. W. Face, J. T. Kucera, D. G. Steel, J. M. Graybeal, T. P. Orlando and D. A. Rudman, *Physica C* **162**, 709, (1989).

"Critical Current Densities in Textured Thin-Films of Bi-Sr-Ca-Cu-Oxide", J. T. Kucera, D. G. Steel, D. W. Face, J. M. Graybeal, T. P. Orlando and D. A. Rudman, *Physica C* **162**, 671, (1989).

"Noise and dc Characteristics of thin-film Bi-Sr-Ca-Cu-Oxide dc SQUIDs", D. W. Face, J. M. Graybeal, T. P. Orlando, D. A. Rudman, *Appl. Phys. Lett.* **56**, 1493 (1990).

"Detection of Ozone Using a Silver-Coated Quartz Crystal Rate Monitor", J. T. Kucera, J. D. Perkins, K. Uwai, J. M. Graybeal and T. P. Orlando, *Rev. Sci. Instr.* **62**, 1630 (1991).

List of Papers Submitted to Refereed Journals but not yet Published:

"Scaling of the Longitudinal and Hall Resistivities due to Vortex Motion in YBCO", J. Luo, T. P. Orlando, J. M. Graybeal, X. D. Wu and R. Muenchausen, submitted to *Phys. Rev. Lett.*

"Anisotropic ac Screening Response in the Vortex State of Superconducting $Bi_2Sr_2CaCu_2O_8$ Crystals", D. G. Steel and J. M. Graybeal, to appear in *Physica C*.

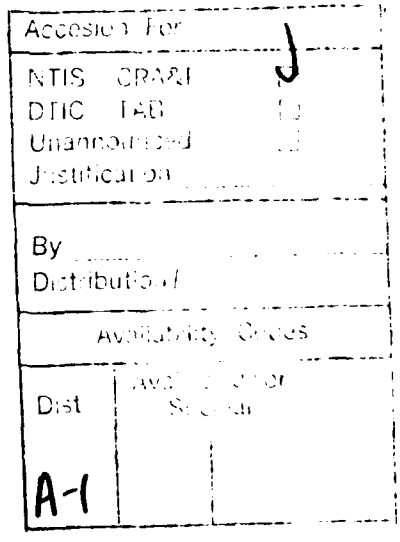
List of Manuscripts in Progress:

"Fabrication of Nanometer-Smooth $Bi_2Sr_2CaCu_2O_{8+\delta}$ Films by Reactive Co-Sputtering from Elemental Targets with Pure Ozone", J. T. Kucera, K. Uwai, L. M. Rubin, J. D. Perkins, J. M. Graybeal and T. P. Orlando.

"ac Screening Response of 2212 BSCCO Crystals", D. G. Steel and J. M. Graybeal.

List of Honors/Awards/Prizes for Contract/Grant Employees:

Prof. John M. Graybeal, Principal Investigator, recipient of an Alfred P. Sloan Research Fellowship, 1989.



Summary of Research Accomplishments

Reactive Sputter Deposition of Bi-Sr-Ca-Cu-O Thin Films

Key achievements:

- Developed process for *in situ* growth of superconducting 2212 BSCCO thin films
- Film top surface smooth on the scale of nanometers - confirmed by STM

Our initial efforts had centered upon *ex situ* annealed films of Bi-Sr-Ca-Cu-O. These previous films were co-sputtered from single-element metallic targets onto substrates held at ambient temperature in the presence of molecular oxygen. Compositions consistent with the 2212 and 2223 BSCCO phases were deposited in this manner. Such films were then *ex situ* annealed in a tube furnace in gas mixtures of Ar-O_2. Anneals as a function of oxygen partial pressure were performed. It was found that the requisite annealing temperatures needed to be close to the bulk melting point to produce films with the bulk value of transition temperature (T_c=85K for $Bi_2Sr_2CaCu_2O_8$ [2212], and 105K for the 2223 phase). It was also observed that it was possible to actually over-oxidize the 2212 films, which resulted in T_c suppressions of up to 10-15K. The 2212 and 2223 films were highly textured, with individual single crystal grains of order 10-20μm. The textured nature of the large grains resulted in a rough film surface with numerous crystalline protrusions, as would be expected from the random nucleation of grains. Critical currents were moderate, reflecting the weak intergranular coupling. X-ray analysis showed that essentially pure 2212 could be formed by such techniques. In contrast, the 2223 was impure, with second phase superconducting 2212 grains. However, relative to the bulk phase, we were able to produce over 50% 2223 in a thermodynamic anneal - bulk synthesis generally requires the addition of Pb in order to achieve such a 2223 volume fraction.

Extensive progress has occurred with our efforts at *in situ* thin-film growth of 2212 Bi-Sr-Ca-Cu-O (BSCCO). Severe problems with the high vapor pressures of some of the constituent metallic elements and their sub-oxides necessitated the conversion from molecular oxygen to the substantially more reactive ozone. An ozone still was built which enabled us to provide a steady stream of pure ozone directly to the heated substrates. A reproducible means of determining the ozone flux was also developed (see details later in this report), which enabled us to supply known (and sufficient) quantities of precision-controlled ozone during the *in situ* deposition process. Difficulties with controlling the flux of metallic constituents

were encountered due to indeterminable amounts of oxide formation on the surface of the individual quartz crystal-oscillator rate monitors for each sputter source. This problem was generally overcome by a combination of composition calibration by Rutherford backscattering plus carefully shrouding of the rate monitors from the reactive ozone. Composition control to within ±5% for each of the 4 metallic elements was possible.

The resultant films were deposited upon heated substrates onto which the sputter sources and ozone flow were directed. Owing to the use of ozone, the background oxygen pressure was unusually low for HTSC deposition, thus substantially reducing oxygen ion ejection from the targets surfaces. Oxygen ions ejected from the targets are accelerated by the target dc bias voltage, and in many cases lead to damage of the resultant films. An additional aspect which reduces the ion ejection problem is our use of triode magnetron sources which generate the requisite plasma with a separate low-voltage filament, and hence do not require large target bias voltages to sustain the plasma.

Typical substrate temperatures of 700°C were used during deposition, with films deposited upon $SrTiO_3$ and MgO substrates. Substrates were rotated during deposition to ensure uniform composition and coverage. After deposition, the films were allowed to cool in a flow of pure ozone. This process yielded films of substantial quality. Transition temperatures in excess of 68K were achieved in *in situ* films, with resistance ratios (R_{300K}/R_{100K}) of 1.5–2. Transport critical currents were performed, with $J_c > 10^6$ amp/cm^2 at 4.2K. These are excellent results for *in situ* BSCCO films. We believe that the reduced resistance ratio is due to inaccuracies in the composition for this line-compound material. The origin of the reduced transition temperature is not fully understood: likely options include over-oxidation (as in the *ex situ* films) and crystalline imperfection arising from off-stoichiometry and/or anti-site substitutions. As pure 2212 was observed in detailed x-ray analysis, with no observed second phases, the possibility of anti-site disorder appears likely. For films compositions sufficiently displaced from stoichiometric 2212, both the x-ray analysis and resistive transitions showed signs of the 2223 phase as a secondary component.

As the *ex situ* films suffered from rough surfaces, extensive analysis of the film smoothness were performed on the *in situ* films. High-resolution scanning electron microscopy (SEM) and scanning tunneling microscopy (STM) were performed. The STM work was performed in collaboration with A. Roshko and J. Moreland of NIST (Boulder, CO). The films were observed to be extremely smooth and featureless, with typical surface roughness of less than 10 nm, as smooth as the best YBCO film.

Detection of Ozone for Reactive Thin-Film HTSC Deposition

Key achievements:

- Developed a new detection technique for *in situ* determination of ozone fluxes, for use with reactive vapor-phase synthesis techniques for fabricating HTSC films
- Obtained measure of detection efficiency

The fabrication of our thin films required the presence of sufficient quantities of reactive oxygen. However, in order to avoid both oxidation of the single-element metallic sputter sources used in our work as well as subsequent ejection of energetic oxygen ions from the targets (which bombard the growing film and cause damage), one obtains upper bounds on maximum desirable oxygen partial pressure. In the case of molecular oxygen, this upper bound is insufficiently low to enable complete oxidation of a BSCCO film during growth. As a result, efforts at *in situ* growth of Bi-Sr-Ca-Cu-O films using molecular oxygen suffered from rapid loss of the high vapor-pressure metallic components (particularly Bi). Therefore, we needed to provide oxygen to the substrate in a more reactive form. The use of ozone had been shown by the University of Minnesota group (Prof. A. M. Goldman) to be an effective oxidant for YBCO thin film growth, and the production, purification (in a liquid nitrogen cooled still) and storage of sufficient quantities of pure ozone is readily feasible with sufficient care.

However, the utility of ozone in *in situ* growth was limited by the inability to obtain a reliable measure of the actual ozone flux at the growth interface. Even if pure ozone originates from the source, ozone is highly reactive and can easily be converted back to molecular oxygen in transit to the thin film. Thus, care must be taken in ensuring that all surfaces contacting the ozone do not catalyze or promote this conversion. Even a relatively inert surface such as teflon or stainless steel can readily recombine ozone if heated even moderately (e.g., 100°C). As the ozone introduction tube to the deposition system must be positioned close to the heated substrates (600-800°C), any tube heating can result in rapid conversion of the reactive ozone into more stable molecular oxygen. Thus, simply knowing the flow of ozone from the ozone generator or purification still is not a reliable measure of the actual ozone flux at the substrate surface.

We therefore developed a technique to directly measure the ozone flux at the substrates, which is akin to techniques previously used for the measurement of atomic oxygen. This technique takes advantage of the known property of silver, in

that silver will not oxidize in the presence of pure molecular oxygen. Thus, by depositing a silver film upon a quartz crystal rate monitor, one can use the mass loading (which the monitor measures) incurred during the silver oxidation process to infer the ozone flux. The only unknown variable is the silver surface reaction probability for ozone on an ambient temperature silver surface (the rate monitor is water-cooled and held in front of the substrates). Our measurements show that the product of the ozone purity and the detection efficiency is 26%, and additional detailed tests are completely consistent with the detection efficiency being very close to 26%. One such cross-check was measuring the phase stability line between the formation of CuO vs. Cu_2O for *in situ* thin film depositions of copper in the presence of ozone.

This therefore provided us with a crucial measure of the ozone flux at the growth surface, enabling us to ensure that sufficient reactive oxygen is available at the growth interface during *in situ* depositions. In our case, the quartz monitor was positioned upon a rotatable positioning arm, which also enabled us to conveniently profile the ozone beam as a function of substrate position. This work was recently published in the *Review of Scientific Instruments.*

Thin-film Bi-Sr-Ca-Cu-O dc SQUIDs

Key achievements:

- Fabrication and detailed noise analysis of BSCCO grain-boundary dc SQUIDs
- SQUID performance comparable to similarly fabricated YBCO devices
- Noise figure not degraded by higher anisotropy of BSCCO

Highly-oriented Bi-Sr-Ca-Cu-O (BSCCO) thin films with T_c in excess of 100K were used to produce thin-film dc superconducting quantum interference devices (SQUIDs). Our work represented the first examination of the noise behavior of BSCCO SQUIDs, and established that their modulation and noise behavior was comparable to equivalently fabricated devices in YBCO. Consequently, we believe that BSCCO films continue to hold promise for SQUIDs and other electronic devices. The known clean surfaces of BSCCO are a distinct advantage over the oxygen-deficient and often insulating surfaces found in YBCO. Of course, BSCCO has known disadvantages, primarily its increased material complexity and higher anisotropy. How these competing factors will play out for various technological applications is still not clear, although we believe that it remains too soon to rule

out BSCCO. In fact, although one might expect higher 1/f noise motion in BSCCO SQUIDs due to the higher anisotropy, this was not observed. Such behavior is consistent with the primary vortex motion occuring *between* grains and not *within* grains.

The starting films were reactive co-sputtered from individual elemental targets in the presence of molecular oxygen, with substrates held at ambient temperature. The films were post-deposition annealed, and contained very large (10-20 μm) single crystal grains. X-ray analysis confirmed that they were mixed phase, containing only the two superconducting BSCCO phases: 2212 (T_c=85K) and 2223 (T_c=105K). On the basis of integrated peak intensities obtained from x-ray analysis, we inferred that the predominant phase present in our films was 2223. No evidence for non-superconducting phases were found.

The devices were patterned by conventional lithographic processing, with an inside loop diameter of ≈18μm and an estimated loop inductance of 30 pH. The devices displayed weak link behavior, and were presumably due to the presence of existing grain boundaries around the SQUID loop. Devices with modulation persisting to 75K were successfully fabricated in this fashion. The effective loop area was determined from the magnetic period of the SQUID modulation, and was found to be basically consistent with the known geometrically defined area of the device, with evidence of "flux focussing" by the surrounding superconducting material. Careful examination of their modulation behavior, plus the conditions for hysteretic and non-hysteretic behavior were studied as a function of temperature and magnitude of the magnetic field sweep. The results of these studies were again found to be comparable to that observed in YBCO grain boundary SQUIDs.

Measurements of the device noise were performed as a function of temperature, frequency and device current bias. The noise was found to obey 1/f behavior over the measured frequency range of 1 Hz-100 kHz. Detailed measurements of the 1/f noise were made at 100 Hz as a function of temperature, resulting in a flux noise of $S_\phi = 1.0 \times 10^{-8}\ \phi_o^2/\text{Hz}$ at 4.8K and $2.3 \times 10^{-7}\ \phi_o^2/\text{Hz}$ at 60K. This noise was almost certainly due to vortex motion between the grains of the film. We note that the voltage probes on our device were placed far from the SQUID loop, and consequently our noise figures also include vortex motion in the current leads. Moving the voltage probes closer to the SQUID ring would no doubt reduce this extraneous vortex noise, and hence improve the noise figure. It is thus interesting to note that despite this problem as well as the increased anisotropy of BSCCO, our measured

modulation and noise amplitude were comparable to that found in similarly fabricated YBCO grain-boundary SQUIDs.

Scaling of Longitudinal and Transverse Hall Resistivities in YBCO

Key achievements:

- Unexpected power-law scaling observed in mixed state of YBCO, linking vortex Hall resistance to longitudinal resistance
- Initial measurements on synthetic multilayers indicates behavior is universal.
- Measurements consistent with recent calculations within vortex-glass model
- Observations provide key confirming evidence for vortex glass model, with measurement of a new critical exponent
- Provides important new insight into vortex state and vortex motion, and significantly advances the present understanding of the vortex Hall effect

We simultaneously measured the longitudinal and transverse resistances due to vortex motion within the mixed state of high-quality superconducting YBCO films. These laser-ablated YBCO films were kindly provided by X. D. Wu and R. Muenchausen of Los Alamos National Laboratory. We observed a remarkable and unexpected power-law scaling of the Hall resistivity $\rho_{xy}(T)$ with the longitudinal resistivity $\rho_{xx}(T)$ as a function of temperature at fixed magnetic field, with $|\rho_{xy}(T)| \propto [\rho_{xx}(T)]^{1.7}$. The consequences of this were explored, and theoretical implications were sought. After detailed interactions with Matthew Fisher (IBM) and Alan Dorsey (Virginia), it was determined that the power-law behavior was consistent with the vortex glass scenario. Our experiments thus provide additional key evidence supporting the contested vortex-glass transition, and may represent the first measurement of a new critical exponent λ_v for the vortex-glass transition. Our experiments also represent the most significant advance in the understanding of the vortex Hall effect in over two decades, and may provide added insight into the nature of vortex motion. This work has been submitted to *Physical Review Letters* in tandem with the theoretical work of Fisher and Dorsey. Additional work on the vortex Hall effect is underway upon model anisotropic superconductor systems consisting of synthetic thin-film multilayers made of alternating layers of superconductive amorphous MoGe and insulating Ge. The principal investigator (JMG) is very familiar with these a-MoGe films, which are extremely well characterized and comprised the material system for his thesis work. The multilayer samples that we

are presently measuring were provided by the group of Professor M. R. Beasley at Stanford University.

In contrast to the wealth of knowledge of the longitudinal resistance for isotropic superconductors in the absence of disorder (pinning), the nature of the transverse Hall resistance is poorly understood. The longitudinal resistance arises from the motion of vortices transverse to the transport current direction, in response to the Lorentz force. Although the existence of a finite Hall resistance clearly implies vortex motion along the current direction, the theoretical understanding of the origin, nature and sign of the vortex Hall effect is very poor. The primary theoretical treatment are old ones due to Bardeen and Stephen, and Nozieres and Vinen. These treatments are hydrodynamic, where the vortices are carried along by the current carriers, and predict a Hall sign in the mixed state which is of the same sign as that observed in the normal state. Behavior consistent with the hydrodynamic model has been observed in a very few disorder-free systems, such as $NbSe_2$. However, numerous measurements have observed radically different behavior in a wide range of materials, including high-temperature superconductors as well as Nb and V, including Hall signs opposite to that observed in the normal state.

High-temperature superconductors, however, are known to be anisotropic and most contain significant disorder (i.e., pinning). Both attributes strongly influence the nature of the vortex state and the vortex dynamics. Considerable theoretical work on the consequences of anisotropy with and without disorder has lead to expectations of a significant enriched phase diagram for the mixed state. Primary theoretical models fall into two categories: entangled vortex states (e.g., D. Nelson, Harvard) which focus on the implications of anisotropy and generally disregard disorder, and the vortex-glass state (e.g., M. P. A. Fisher, IBM) which includes both aspects. Thus, considerable attention has been directed to examining the vortex dynamics, principally upon the longitudinal resistance. We emphasize that any thorough understanding of the vortex dynamics must encompass both the longitudinal and Hall resistances. As it similarly involves the vortex motion, the Hall resistance should be seen as holding significant potential for further insight into the nature of the vortex state.

We were able to separate the riddle of the vortex Hall effect into two parts. The first question is what is the *functional dependence* of the vortex Hall effect in three-dimensional superconductors in the presence of pinning. The second question is what is the *origin of the negative (opposite) sign* which is frequently observed in the vortex Hall signal. By separating the problem in this manner, we were thus able to

provide significant insight into the first question, and provided a new possibility to explain the second.

In addressing the first question, our key observation was the power-law dependence of $|\rho_{xy}(T)| \propto [\rho_{xx}(T)]^{1.7}$ at fixed magnetic field. This represents the first observation of *any* clear dependence for the vortex Hall resistivity, other than the Bardeen-Stephen behavior predicted in the absence of disorder (i.e., linear $V_{xx}=IR_{xx}$ and $V_{xy}=IR_{xy}$, with R_{xy}/R_{xx}=constant). This observation thereby provided a clear link between the previously poorly understood Hall behavior to the longitudinal response, where significantly more theoretical effort has occurred.

In particular, in YBCO it has been observed (R. Koch, *et al*) that the longitudinal resistivity is consistent with predictions of the vortex glass model (M. P. A. Fisher). In three-dimensional superconductors, the vortex-glass model leads to a true zero resistance state at finite fields, unlike that predicted by the hydrodynamical Bardeen-Stephen model in the absence of disorder. Specifically, the vortex-glass model predicts a divergent length for vortex correlations, $\zeta(T,H)\sim(T-T_g(H))^{-\nu}$, a divergent time for the motion of these correlated regions, $\tau\sim\zeta^z$, and a corresponding zero-bias longitudinal resistivity of $\rho_{xx}\sim(T-T_g)^{\nu(z+2-D)}$ as $T\rightarrow T_g+$. Here ν and z are critical exponents, and D is the dimensionality. The vortex-glass model only predicts a finite-temperature transition for dimensionality *greater* than two, i.e., 2D is the critical dimension for the vortex-glass. For an anisotropic superconductor (within the Lawrence-Doniach model), the ratio of the correlation transverse to the vortex $\zeta_\perp$ to the correlation length along the vortex ζ_z is given by the anisotropic mass ratio $\gamma=M/m$.

Motivated by our results, Fisher and Dorsey made a scaling theory for the vortex Hall effect within the vortex-glass model. Note that such a scaling analysis need not know the origin or the sign of the Hall signal, it only requires that it exists. Their scaling calculation thus confirmed that a power-law behavior should be observed, with an exponent greater than one. Subsequently, by reviewing our I-V_{xx} measurements, we obtained the correlation lengths in our films, and showed that our data was consistent with being within the critical regime of the vortex-glass transition. The critical regime in three dimensions corresponds to the case where $a_H<\zeta_\perp$ and $\zeta_z<d$, where a_H is the average vortex spacing and d is the sample thickness. Within this treatment, our data presents the first measurement of the critical exponent λ_ν, and provides important evidence for the validity of the vortex-glass state.

In yet unpublished initial measurements in MoGe/Ge multilayers, we have observed for the three-dimensional regime the *same* power-law behavior with

exponent α=1.7. Furthermore, this observation was in the *positive* Hall regime, which provides added evidence for the model of Fisher and Dorsey and indicates that the power-law exponent is universal. Similar initial measurements on single two-dimensional MoGe films appear consistent with an exponent of about one. This latter result is also interesting, as earlier work on 2212 BSCCO single crystals observed identical simple activated behavior in $\rho_{xx}(T)$ and $\rho_{xy}(T)$. This observation of identical activation energies was in the temperature range where the vortices are now thought to be two-dimensional. If true, such behavior would imply a power-law behavior with α=1. Note that two dimensions is thought to be the critical dimensionality for the vortex-glass transition.

As to the second question, what is the origin of the negative Hall effect, our results provide additional clues. It is important to notice that all models preceding our results simply modified the original hydrodynamic treatment. It is thus worthwhile to review the assumptions of the hydrodynamical models. The hydrodynamic model assumes *no* disorder, assumes *steady-state* motion, and *ignores* the microscopic details within the vortex cores. We believe that the one of these assumptions is invalid, and we thus come to the following crossroads. Either the microscopic details internal to the vortex (i.e., band structure) strongly modify the behavior from that predicted by the hydrodynamic model, or disorder is the key, or both. Note that if such band structure effects are crucial, a negative Hall sign should thus be expected to arise even in the absence of disorder. Of course, the microscopic details of the excitations of the vortex are also sensitive to disorder. We note that multiple sign changes in the vortex Hall signal are observed in many HTSC systems as a function of field and temperature, which to us appears difficult to explain via band structure effects alone.

The relevance of disorder is a new possibility that we wish to introduce to the discussion. Specifically, it is clear that vortex motion is strongly modified by the pinning potential. Furthermore, it is worth noting that in the presence of disorder the vortex motion between potential "wells" is strongly time-dependent and thus may not reach steady state. In such a case, the resultant "dc" behavior might actually be the time average of repeated transients, not a steady-state result. An alternative and very interesting possibility is that in the presence of pinning, the moving objects are not vortices but *defects*. One can make analogies to compensated semiconductors, with heavy electrons and light holes, although there are important differences. In the compensated semiconductor, there are only holes - which for the superconductor is the equivalent to an anti-vortex. However, at the magnetic field

levels used for our measurements, the density of anti-vortices is extremely small. Additionally, the sign found in Nernst effect measurements (equivalent of thermopower for a semiconductor) appear to rule out anti-vortices as the source of the negative Hall signal. Yet a three-dimensional superconductor has a myriad of other defects existent in the vortex state, including dislocations, disclinations, and vortex loops. Little is known about how such defects move. If they should prove more mobile than the strongly pinned vortices, it would clearly be very important as it would also comprise the origin of the longitudinal resistance as well. The origin of the sign for the vortex Hall resistance thus continues as a very important question, and the motion of such defects emerges as a key research issue for the future.

Measurement of the ac Screening Response of 2212 BSCCO Crystals

Key achievements:

- Observation of systematic dispersion in the temperature T^* of the apparent "dissipation peak" found in finite-frequency χ' susceptibility measurements
- Determination of the origin of the dissipation peak
- Rules out previous claims of a phase transition (either melting or otherwise) in the temperature range of 40-50K for 2212 BSCCO

Numerous researchers have observed apparent dissipation peaks and irreversibility lines in the range of 40-50K for 2212 BSCCO crystals in the presence of modest fields (e.g., 0.1-40 kOe). The original work from the AT&T group (D. J. Bishop, *et al*) on BSCCO crystals mounted upon high-Q silicon torsional oscillators observed apparent sharp peaks in the dissipation for the temperature range of 40-50K, and presented this as convincing evidence for a melting transition of the vortex lattice. Their oscillator operated in the range of 1-2 kHz, with a $Q \approx 10^6$. Such behavior has since been seen in this same temperature range by numerous other workers, including resistive transitions as well as irreversibility lines from magnetization measurements. It is important to note that the Bell work was arguably in the linear response regime, whereas a considerable fraction of the irreversibility line work involves highly non-equilibrium and inherently nonlinear vortex response.

We built a sensitive ac susceptometer capable of operating at a wide range of frequencies (1 Hz$<\omega<$100 kHz) which could enable ac susceptibility measurements of BSCCO crystals either parallel or perpendicular to an externally supplied dc magnetic field. The susceptometer was quite sensitive, enabling the use of extremely

low ac modulation amplitudes (0.1-5 mOe). We were thus able to ensure that our measurements were in the linear response regime, as dispersion was observed with increasing ac modulation. Although measurements were made as a function of direction with respect to the crystalline axes and applied magnetic field, I will focus on the results for the configuration with both ac modulation and dc field aligned perpendicular to the Cu-O planes. Use of a phase-sensitive lock-in amplifier for the output signal allowed simultaneous measurement of the real and imaginary parts of the susceptibility, i.e., $\chi = \chi' + i\chi''$.

At a given frequency and dc applied field level, $\chi''(T)$ was observed to display an apparent sharp "dissipation peak" at a temperature we shall call $T^*(H)$. For frequencies in the range of 1-2 kHz, values for $T^*(H)$ were found to be consistent with the previous Bell work. However, as we varied the ac modulation frequency over the range of $1\text{-}10^5$ Hz significant dispersion in T^* was observed. Indeed, as the modulation frequency was reduced to 1-10 hz, T^* was observed to decrease by 10-15K or more. Such behavior is completely inconsistent with any form of a phase transition in the neighborhood of 40K, as the transition temperature *must* be obtained in the limit of $\omega \rightarrow 0$. Furthermore, for dc fields in the range 0.1-10 kOe, cautious extrapolation of our data to zero frequency appears to place an upper bound of order 25K for any transition.

Such dispersion naturally leads to questions regarding the origin of the observed "dissipation peaks" at finite frequency. Is the peak reflecting intrinsic dispersion due to low-frequency displacive modes in the vortex system, or is there another explanation? We have completed a series of detailed measurements as a function of frequency, dc field and temperature which show convincingly that the origin of this dissipation peak is due to finite-size screening effects..

Simply stated, the origin of the observed dissipation peak is due to skin depth effects, due to the finite dissipation in the crystals due to vortex motion. Such vortex motion implies a finite resistivity $\rho(T,H)$, from which one can infer an electromagnetic screening length $\delta \propto (\rho/\omega)^{1/2}$ as in any metal. At temperatures above T^* (but still below T_c), vortices are quite mobile leading to sizable resistivity. From ρ one obtains the screening length δ which is less than the characteristic sample size L. Hence, in this range the measured signal does *not* reflect the entire sample volume, but only a ring of width δ around the sample circumference. As the temperature is reduced towards T^*, the resistivity drops and correspondingly δ increases. Hence, the apparent dissipation χ'' increases as the ac field measures an ever larger fraction of the sample volume. Finally at T^*, $\delta \approx L/2$, and the ac modulation measures the

entire sample - leading to a maximum in the observed dissipation signal. As T decreases below T^*, the screening length $\delta > L/2$ and the entire sample continues to be probed. However, since the vortices are less mobile with decreasing temperature, ρ also decreases, leading to a reduction in the measured χ' - hence the apparent "dissipation peak". At frequencies and fields where we were able to measure the dc resistance of the sample, we observed that the inferred T^* corresponded to where the inferred screening length δ was constant and of order $L/2$. This confirms the electromagnetic screening origin of the observed peak.

Consequently all previous claims of a melting transition on the basis of "dissipation peaks" are incorrect. In fact, such susceptibility measurements are actually a very sensitive measure of the sample resistance, able to measure extremely low resistivities otherwise unmeasurable without the aid of a SQUID voltmeter. Of course, such resistivity is due to vortex motion. Only in the limit of $\omega \rightarrow 0$ would such measurements be able to address the existence of a phase transition to a vortex solid or glass. A written manuscript describing this work is presently in preparation, and will soon be submitted for publication.

Flux Creep and High-Field Critical Currents in YBCO

Key achievements:

- The first detailed study and verification of large anisotropic critical currents in epitaxial YBCO thin films
- For high fields and temperatures at or above 77K, thermally-activated flux flow can in large part explain the magnitude plus the temperature and field dependence of the critical currents in YBCO

In this early work, detailed measurements were made of the current-voltage behavior of high-quality epitaxial YBCO thin films in the presence of large applied fields. This work was done in collaboration with the groups of Profs. Skocpol and Brooks at Boston University, plus Drs. P. Mankiewich and R. E. Howard at AT&T Bell Labs (Holmdel), and was published in *Physical Review Letters*.

Detailed measurement of the critical currents as a function of angle between the field and the Cu-O planes resulted in the observation of large critical current densities J_c for these films. Even in the *least* favorable orientation ($B \perp$ Cu-O planes), J_c values in excess of 5×10^5 amp/cm^2 were observed at fields of 15 tesla at 20K. Clearly this makes YBCO an important candidate for high-field operation. How-

ever, important questions existed (and still persist, although at lower temperatures) as to the nature of the vortex state and the origin of the vortex motion, particularly in the presence of large applied currents. Our measurements provided one of the first detailed analyses of these issues.

From detailed I-V measurements, we were able to infer the field and temperature dependence of basic parameters related to vortex pinning, such as the vortex pinning force F_p, activation energy U, and magnetic field $B^*(T)$ for the maximum pinning force. For this range of field and temperatures, which are above the apparent vortex-glass transition, we showed that the detailed dependences of F_p and B^* as a function of temperature and/or field are consistent with basic thermally-activated vortex motion using the model of Tinkham. Tinkham's model basically assumed that the primary energy scale setting the pinning force is distortions in the local vortex configuration, and estimated them from calculations of the shear modulus in pinning-free systems. In the comparison with experiment, the primary free fitting parameter is the logarithm of the intrinsic vortex attempt rate. The fits to the data yielded consistent values for this attempt rate from both the temperature dependences of F_p and B^*, and additionally were found to be physically reasonable.